Journal of Environmental Management 92 (2011) 223–228

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar

Mustafa K. Hossain [a,*], Vladimir Strezov [a], K. Yin Chan [b], Artur Ziolkowski [a], Peter F. Nelson [a]

[a] *Graduate School of the Environment, Faculty of Science, Macquarie University, NSW 2109, Australia*
[b] *NSW Industry and Investment, Locked Bag 4, Richmond, NSW 2753, Australia*

ARTICLE INFO

Article history:
Received 21 December 2009
Received in revised form
6 August 2010
Accepted 6 September 2010
Available online 27 September 2010

Keywords:
Wastewater sludge
Biochar
Pyrolysis
Nutrients

ABSTRACT

The important challenge for effective management of wastewater sludge materials in an environmentally and economically acceptable way can be addressed through pyrolytic conversion of the sludge to biochar and agricultural applications of the biochar. The aim of this work is to investigate the influence of pyrolysis temperature on production of wastewater sludge biochar and evaluate the properties required for agronomic applications. Wastewater sludge collected from an urban wastewater treatment plant was pyrolysed in a laboratory scale reactor. It was found that by increasing the pyrolysis temperature (over the range from 300 °C to 700 °C) the yield of biochar decreased. Biochar produced at low temperature was acidic whereas at high temperature it was alkaline in nature. The concentration of nitrogen was found to decrease while micronutrients increased with increasing temperature. Concentrations of trace metals present in wastewater sludge varied with temperature and were found to primarily enriched in the biochar.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Wastewater sludge is a byproduct of the wastewater treatment process and is composed of organic compounds, macro and micronutrients, trace elements, micro organisms and micro pollutants. The high concentration of phosphorus and nitrogen in wastewater sludge as well as other micro and macro nutrients, has been the primary reason for the application of wastewater sludge for cultivation of crops (Sumner, 2000; Singh and Agrawal, 2008). Generally, nitrogen is the land limiting constituent when municipal wastewater sludge and animal wastes are applied to the soil (Overcash et al., 2005). The total nitrogen in wastewater sludge is variable and may range from <0.1 to 18% with a median of 3.3% and the level of mineral nitrogen may reach up to 6.7% (Sommers, 1977). The composition of the sludge varies remarkably over time from a given treatment facility because most of the nitrogen in sludge is in organic form (Magdoff and Chromec, 1977; Sommers, 1977). Mineralisation of organic N is dependent on type of organic material, rate of application, soil type, water content of the soil and soil temperature (Clark and Gilmour, 1983; Parker and Sommers, 1983; Barbarika et al., 1985). Beside the nitrogen content, wastewater sludge also is a source of phosphorus. The concentration of phosphorus in the sludge is variable and may vary from less than 0.1% to 14% on dry weight basis depending on the nature of the raw sludge and the treatment process (Sommers, 1977). McLaughlin (1984) reported variations in the forms of phosphorus in sludge depending on the composition of the raw sludge and type of the wastewater treatment process. Phosphorus in the sludge is mostly present in an inorganic form and its bioavailability depends on the compounds used for sludge stabilisation (Joao et al., 1997). The plant available phosphorus in sludge varies between 25 and 40% compared to inorganic phosphorus. McLaughlin and Champion (1987) showed that phosphorus in the sludge acts as a slow release P fertiliser in the sesquioxic P deficient soils. On the other hand, phosphorus accumulation in soils through application of sludge could have adverse environmental impacts on surface and ground water through leaching (Sumner, 2000). Sewage sludge is also enriched with metals, such as Cr, Cd, Cu, Ni, Se and Zn, pathogens and low concentration antibiotics, which are of the major concern limiting its potential use as a fertiliser (McBride, 1995; Overcash et al., 2005; He et al., 2010).

Conversion of organic materials to biochar through pyrolysis supports an alternative way to manage a range of wastes (Hospido et al., 2005; Bridle and Pritchard, 2004; Strezov and Evans, 2009). Pyrolysis of wastewater sludge can potentially be a method of choice for its management, particularly compared to the current

---

[*] Corresponding author. Tel.: +61 2 9850 7978; fax: +61 2 9850 7972.
E-mail address: kamal.hossain@mq.edu.au (M.K. Hossain).

0301-4797/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2010.09.008

methods of landfilling and direct agricultural utilisation (Hwang et al., 2007) as this process reduces the volume of the solid residue, eliminates pathogens and organic compounds of concern present in the sludge (Caballero et al., 1997; Koch and Kaminsky, 1993).

Biochars are carbon rich materials that contain a range of plant nutrients and can be valuable as soil amendments. The chemical composition of the biochar depends on the source of feedstock and pyrolysis conditions (Chan and Xu, 2009). The concentration of nitrogen and/or phosphorus in the sludge may be reduced by the pyrolysis conditions through the evolution of higher molecular weight volatiles, while the concentration of metals present in the biochar is expected to increase. Biochar yield also varies significantly depending on the production procedure, processing and source properties (Lehmann et al., 2006). Numerous studies have been conducted on pyrolysis of biomass as a potential energy source (Chan and Xu, 2009; Tsai et al., 2006; Horne and Williams, 1996). Less attention has been given to the effect of pyrolysis on biochar properties especially on the total nutrient concentration and their availability (Chan and Xu, 2009).

The aim of this work is to investigate the influence of pyrolysis temperature on the production and nutrient properties of wastewater sludge biochar.

2. Experimental

2.1. Wastewater sludge materials

Digested wastewater sludge sample was collected from an urban wastewater treatment plant in the Sydney region. The sampling was conducted three times at a regular interval from the same batch to make a composite sample. The wastewater sludge sample used in this work was first dried at room temperature and then separated from other physical impurities, such as small fraction of leafs and plastic bags. The sample was then dried at 36 °C for two days and stored in air tied plastic bags until pyrolysed. The sample was pyrolysed under controlled pyrolysis conditions to ensure uniform heating and treatment. Biochar production was carried out using a fixed bed horizontal tubular reactor with dimensions of 3.5 cm in diameter and 16 cm in length, set at a heating rate of 10 °C min^{-1} at four peak temperatures of 300 °C, 400 °C, 500 °C and 700 °C. Nitrogen gas set at 50 L/min was flown through the reactor and the offgas was passed through a water cooling chamber which condensed the heavy tars. Biochar production at each temperature was replicated four times. The quantity of feedstock used for the pyrolysis was in the range of 264–273 g. The percentage of biochar yield at various temperatures was calculated from the mass of the original sludge and the weight of the produced biochar after completion of the pyrolysis.

2.2. Chemical analysis

The composition of the wastewater sludge sample used in this study was assessed on air dried basis using proximate and ultimate analysis tests according to the Australian standard AS1038 method. The chemical analysis of the biochar was undertaken in a NATA (National Association of Testing Authorities, Australia) accredited facility using ISO17025. Total C and N were measured by Dumas combustion method using an ELEMENTAR Analysensysteme Vario MAX CN analyzer with combustion chamber set at 900 °C and oxygen flow rate of 125 ml min^{-1}. The pH was measured in 0.01 M $CaCl_2$ (1:5) according to method 4B2 of Rayment and Higginson (1992). Available phosphorus (Colwell), mineral nitrogen (KCl extraction) and DTPA-extractable micronutrients were measured according to methods 9B1, 7C2 and 12A1 of Rayment and Higginson (1992) respectively. For elemental compositions and metals analysis, 0.25 g dried and ground sample is weighed into a microwave vessel. Nitric acid and peroxide are added and the sample is digested using microwave assisted acid digestion. Samples are made up to 25 ml with type 1 water and analyzed by ICP-AES according to USEPA 6010 method.

2.3. FTIR analysis

The Fourier Transformation Infrared (FTIR) spectra of powdered samples were recorded in Nicolet 6700 FTIR spectrometer applying Attenuated Total Reflectance (ATR) method with diamond crystal. The total number of scans was 32 with spectral resolution of 4 cm^{-1}. Omnic Spectra software was used to assist with interpretation of some of the data.

2.4. Statistical analysis

Univarite analysis (ANOVA) and post-hoc Student–Newmans–Kules (SNK) test were performed using GMAV5 (Underwood and Chapman, 1989) to determine the significance of differences in the concentrations of the elements in the wastewater sludge biochar produced at different temperatures. Data was tested for homogeneity of variance using Cochran's test.

2.5. Relative enrichment of elements in biochar

To understand the volatile nature under combustion conditions, relative enrichment (RE) factors are calculated:

$$\text{RE} = \frac{\text{Elemental concentration in biochar}}{\text{Elemental concentration in sludge}} \times \frac{\text{biochar yield}}{100}$$

Relative enrichment factors help to identify the degree of enrichment of elements in the biochar and reveal the volatility of trace elements. RE factors in biochar greater than 1 indicate larger enrichment of the trace element in the biochar, while when RE factors are less than 1 then the elements exhibit volatilisation.

3. Results and discussion

3.1. Biochar yield

Biochar yield decreased with increasing pyrolysis temperature from 72.3% of the original feedstock mass at 300 °C, 63.7% at 400 °C, 57.9% at 500 °C and 52.4% at 700 °C (Table 1). The rate of weight loss was the most rapid at 300 °C, which is the temperature of torrefaction, losing approximately 27% of the initial mass. At temperatures from 300 °C to 400 °C the biochar yield decreased by 8.6%, while heating from 500 °C to 700 °C decreased by additional 5%.

3.2. Changes in chemical bond structure with pyrolysis temperature

The infrared spectra of the sludge and biochar samples, revealed their complex chemical bond structure consisting of mixture of mineral and organic matter (Fig. 1). The two sharp peaks at about 3700 cm^{-1} and 3600 cm^{-1} corresponding to vibration of OH groups in the mineral matter. Unlike OH and NH vibrations which come

Table 1
Means and standard errors of biochar yields produced at different temperatures.

	300 °C	400 °C	500 °C	700 °C
Biochar yield	72.3% ±2.5	63.7% ±2.0	57.9% ±2.3	52.4% ±2.6

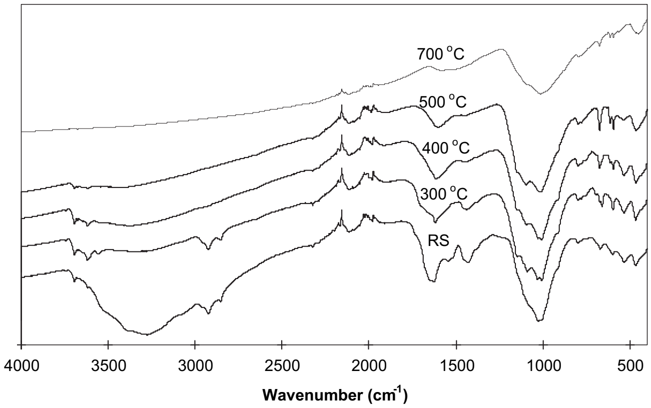

Fig. 1. FTIR spectra of wastewater sludge and sludge biochar prepared at different temperatures (RS – raw sludge).

Table 2
Proximate, ultimate and agronomic properties of wastewater sludge and sludge biochar at various temperatures.

	Unit	Wastewater sludge	Sludge biochar			
			300 °C	400 °C	500 °C	700 °C
Moisture	%	7.6	4.3	4.2	3.5	3.4
Ash	%	34	52.8	63.3	68.2	72.5
FC	%	8.2	9.1	6.8	7.6	8.3
VM	%	50.2	33.8	25.7	20.7	15.8
C	%	32.3	25.6	20.2	20.3	20.4
H	%	4.47	2.55	1.28	0.88	0.51
N	%	3.27	3.32	2.40	2.13	1.20
O	%	18.36	8.33	4.61	0.65	0.00
pH	pH Unit	4.42	5.32	4.87	7.27	12
EC	ds m^{-1}	11.95	4.12	4.15	4.7	2.5
Colwell P	mg kg^{-1}	747.5	492.5	740	567.5	527.5
KCl extrac. NH_4-N	mg kg^{-1}	7275	1175	142.5	25	1.34
KCl extrac. NO_3-N	mg kg^{-1}	35	<0.2	<0.2	0.24	0.32

FC = fixed carbon, VM = volatile matter, O% calculated by difference.

from organic matter (maximum peak at 3276 cm^{-1}) the inorganic OH groups are still detected in the sample treated at 700 °C. The intensity of peak at 3276 cm^{-1} decreases rapidly from raw material sample to sample heated at 300 °C suggesting that organic OH and NH groups are very unstable at elevated temperatures. The bands at 2954 cm^{-1} and 2847 cm^{-1} correspond to aliphatic CH_3 asymmetric and symmetric stretching vibration respectively, which are also confirmed by scissoring CH_2 vibration at 1432 cm^{-1}. These bands are absent in samples heated at 400 °C and above. Methyl groups (CH_3) similar to OH and NH groups are the weakest functional groups and break at low temperatures. The cleavage of these groups is contributing to higher mass loss during thermal decomposition and gas product evolution. The stretching vibration of C–H bond in aromatic structures is visible as a band at around 2924 cm^{-1}. Aromatic and heteroaromatic compounds are also confirmed by C–H wagging vibrations in the region between 800 and 600 cm^{-1}. The intensity of these peaks increases for samples treated at 300 °C and higher temperatures which indicates stability of the aromatic and heteroaromatic compounds and possible cyclisation. Presented results suggest that decomposition of nitrogen organic structure, such as amine and amides, takes place at temperature below 300 °C. The broad band corresponding to vibration of O–H groups at around 3390 and C–N–C bending vibration at 1544 cm^{-1} are present only in raw samples. The bands below 600 cm^{-1} are due to M–X stretching vibrations in both organic and inorganic halogens compounds (M-metal, X-halogen). The main difference between the FTIR spectra of the wastewater sludge biochar from this work and biochars produced from woody materials (Mulligan et al., 2010), is in the presence of organic nitrogen and metallic compounds in the sludge biochar.

3.3. Agronomic properties

As expected pyrolysis temperature affected the agronomic properties of wastewater sludge biochar as shown in Table 2. The volatile matter decreased from 50.2% for the raw sludge, 33.8% for the biochar prepared at 300 °C to 15.8% at 700 °C. The fixed carbon was in similar order for all samples, while the ash concentration in the biochar significantly increased with the pyrolysing temperature.

The biochar was acidic when produced at lower treatment temperatures, shifting to alkaline at 700 °C. At 500 °C the pH of the biochar was almost neutral (7.27). The electrical conductivity (EC) increased slowly with temperature of up to 500 °C but at higher temperatures it was reduced by almost a half. The electrical conductivity, a parameter used to estimate the amount of total dissolved salts in the sample, was 11.95 dS m^{-1} for the raw sample, while significantly decreasing with the pyrolysis temperature.

3.4. Major nutrients

The amount of total N and NH_4-N was found to be higher for low treatment temperatures and decreased with temperature (Table 2). Rapid loss of organic OH and NH groups from organic matter of wastewater sludge for temperature above 400 °C was also confirmed by the FTIR spectra (Fig. 1). Available phosphorus (Colwell P) was high at 400 °C and decreased with the temperature. Pyrolysis temperature had little effect on NO_3-N, at 300 °C and 400 °C measuring below the detection limit, however above 500 °C it increased by small amounts.

3.4.1. Nitrogen

Total N content of wastewater sludge biochar decreased by 55% when the temperature was increased from 300 °C to 700 °C (Fig. 2). This may be due to the volatilisation of nitrogen during pyrolysis (Bagreev et al., 2001; Gaskin et al., 2008). Shinogi (2004) also reported a decrease of total N in the biochar produced from sewage sludge at higher temperatures. Nitrogen is removed through loss of the NH_4-N and NO_3-N fraction as well as the loss of volatile matter containing N groups at temperature of 200 °C, but with increased temperature (>600 °C) it is gradually transformed into pyridine like structure (Bagreev et al., 2001). Our study indicates that relatively high proportion of nitrogen is still conserved at low pyrolysis

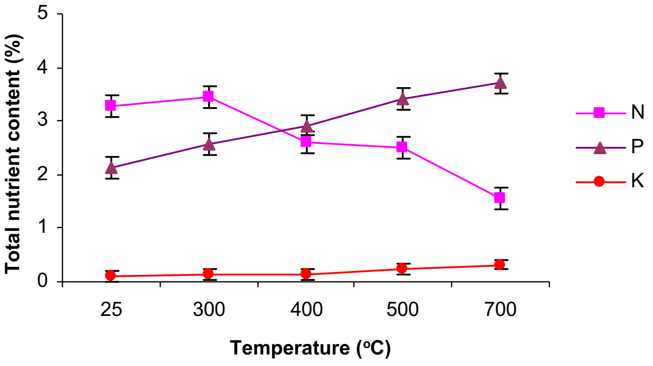

Fig. 2. Changes in total N, P and K concentration in wastewater sludge samples and to produce biochars at different temperatures. Values at 25 °C indicate the raw wastewater sludge. All other temperatures indicate wastewater sludge biochar concentrations.

Table 3
Means, standard deviations and RE factors for the total nutrient concentrations of wastewater sludge and biochars.

Elements	Description	Units	RS	300 °C	400 °C	500 °C	700 °C
Ca	Mean	%	3.02	3.47	4.17	4.62	5.35
	SD		±0.06	±0.15	±0.02	±0.12	±0.10
	RE			0.8	0.9	0.9	0.9
Fe	Mean	%	6.17	7.8	8.85	10.15	11
	SD		±0.06	±0.09	±0.08	±0.28	±0.00
	RE			0.9	0.9	0.95	0.95
Mg	Mean	%	0.33	0.35	0.43	0.46	0.54
	SD		±0.01	±0.01	±0.01	±0.01	±0.01
	RE			0.8	0.8	0.8	0.9
S	Mean	%	5.17	4.47	4.72	5.9	6.17
	SD		±0.02	±0.15	±0.04	±0.19	±0.19
	RE			0.6	0.6	0.7	0.6
Cu	Mean	mg kg^{-1}	810	1150	1125	1325	1500
	SD		±12.90	±28.86	±25	±25	±70.71
	RE			1	0.9	0.9	1
Zn	Mean	mg kg^{-1}	1350	1675	1825	2100	2175
	SD		±28.86	±25	±25	±0.00	±25
	RE			0.9	0.9	0.9	0.8

RS = raw sludge; SD = standard deviation; RE = relative enrichment factor; ±0.00 indicates results were near instrument detection limit.

temperatures (Fig. 2). The ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) are important agronomic properties because these are the main sources of available N for plant uptake. The NO_3-N present in the studied biochar samples is very low ranging from less than detection limit (0.2) to 0.32 mg kg^{-1} (Table 2). Ammonium nitrogen concentrations in biochar are higher than NO_3-N. Ammonium nitrogen concentrations decreased rapidly with increasing temperature. Ammonium nitrogen at 300 °C measured at 1175 mg kg^{-1} was reduced to 143 mg kg^{-1} at 400 °C, suggesting that available nitrogen content in the form of NH_4-N is higher in wastewater sludge biochars produced at lower pyrolysis (<400 °C) temperatures. It is very unlikely that total N present in the biochar is fully available for plant uptake as it is organically bonded in recalcitrant forms (Chan and Xu, 2009). While there is limited data on the plant availability of nitrogen in biochars, previous work conducted by Chan et al. (2007) on poultry litter biochar found only 2 mg kg^{-1} of available nitrogen (NH_4-N plus NO_3-N), which is in the same range as the nitrogen measured at the higher pyrolysis temperatures in this work.

3.4.2. *Phosphorus*

The total P content in the wastewater biochar increased by 43% when pyrolysed at a temperature of 700 °C indicating phosphorus is associated with the inorganic fraction of the wastewater sludge (Fig. 2). This finding showed similar increasing trend to the reported increase of phosphorus with temperature from 5.6% at 250 °C to 12.8% at 800 °C in biochar produced from sewage sludge (Chan and Xu, 2009). Bridle and Pritchard (2004) also discussed the full recovery of P in biochar produced from sewage sludge at 450 °C. Concentration of P in the wastewater sludge biochar will depend on the wastewater treatment process. For example during primary sedimentation phosphate is removed primarily by settling of insoluble precipitates and therefore primary sludges contain mostly inorganic P forms (Pastene, 1981). The wastewater sludge sample in this work was a sludge produced after a secondary treatment process, hence the phosphorus content was low. The plant available P (Colwell phosphorus) in the biochar varied from 492.5 mg kg^{-1} to 527.5 mg kg^{-1} at a temperature of 300 °C and 700 °C respectively.

3.4.3. *Potassium*

A very little amount of total potassium was present in the wastewater sludge biochar (Fig. 2). Potassium was found to increase in concentration with increasing temperature mainly because of the inorganic association of potassium with the wastewater sludge. Biosolids commonly contain small amounts of K (0.1–0.6%) as indicated previously by Cogger et al. (2006).

3.5. *Other nutrients*

Table 3 shows that total concentration of the other nutrient elements present in the wastewater sludge and sludge biochar. The nutrients Ca, Fe and Zn significantly increased with increasing pyrolysis temperature. There are no significant differences in the total concentration of Cu between the temperature of 300 °C and 400 °C but concentration varies significantly between the biochars produced at temperatures 400 °C, 500 °C and 700 °C. In the case of Mg concentration varies significantly for biochars produced at 300 °C and 400 °C and 500 °C and 700 °C. The concentration of S varies significantly only between the temperatures of 400 °C and 500 °C. The variability of the micronutrients with temperature is due to their volatility and effect of pyrolysis temperature on both composition and chemical structure of the biochar (Chan and Xu, 2009). Considering relative enrichment factors for the elements from Table 3, sulphur exhibited the highest volatility losing 40% of its initial sulphur content, while Cu exhibited almost insignificant volatility.

3.6. *Trace elements*

A range of trace elements present in the biochar are shown in Table 4. The concentration of As and Se was below the detection limit in the sludge and all biochars. The concentrations of all the other elements were significantly higher in the biochar samples than raw sludge (Table 4). Concentration of Cd in the biochar was found to increase with increasing temperature. Concentration of Pb, Ni and Cr was enriched in the biochar at temperatures of up to 500 °C then they decreased at 700 °C indicating partial defractionation and/or devolatilisation of these metals at elevated temperatures. RE factors indicated the largest volatility for Cr at 700 °C with a loss of 50% of its initial concentration.

3.7. *DTPA available metal elements*

The trace elements present in biochar may not be entirely available for plant uptake. DTPA (diethylene triamine pentaacetic

Table 4
Means, standard deviations and RE factors for total metal concentrations in mg kg^{-1} present in wastewater sludge and biochars.

Metals		RS	300 °C	400 °C	500 °C	700 °C
As		<3	<3	<3	<3	<3
Cd	Mean	2.07	2.62	2.8	3.17	3.22
	SD	±0.06	±0.04	±0.05	±0.12	±0.06
	RE		0.9	0.9	0.9	0.8
Cr	Mean	81	107.5	112.5	112.5	83
	SD	±0.70	±2.50	±2.50	±2.50	±3.36
	RE		1	0.9	0.8	0.5
Ni	Mean	70	182.5	165	292.5	195
	SD	±0.91	±18.42	±11.9	±34.24	±6.45
	RE		1.9	1.5	2.4	1.5
Pb	Mean	86.5	115	130	140	132
	SD	±1.04	±2.88	±0.00	±0.00	±2.5
	RE		1	1	0.9	0.8
Se		<6.6	<6.6	<6.6	<6.6	<6.6

RS = raw sludge; SD = standard deviation; RE = relative enrichment factor; ±0.00 indicates results were near instrument detection limit.

acid) extraction method is a technique used to estimate the readily available concentration of elements for plant uptake. In this work the availability of some trace elements (Cd, Cu, Fe, Mn and Zn) in biochars was compared for different pyrolytic temperatures using this method (Table 5).

DTPA-extractable concentrations of all the elements (with the exception of Fe) in the biochars were lower than those in the original raw wastewater sludge samples. The process of pyrolysis appears to reduce the bioavailability of many of these trace elements. The greatest DTPA Cu concentrations were seen at 400 and 500 °C. The highest availability of Fe and Zn was detected at a temperature of 300 °C and decreased with increasing temperature. Considering the total concentration of these two elements is enriched in the biochar (Table 2), results of the DTPA test suggest that high pyrolysis temperature reduces bioavailability of Fe and Zn. The available concentration of Mn is significantly different between the temperature of 300 °C and 400 °C but there is no significant difference between 400 °C and 500 °C. The bioavailable concentration range of Cu and Cd is low for almost all temperatures. Availability of Cu at temperatures of 300 °C and 700 °C and Cd for all temperatures except for 400 °C was below the detection limit. Variation in the DTPA concentration with increasing temperatures of these trace elements reflects the changes in their chemical forms during the pyrolysis process.

Table 5
Means, standard errors and RE factors for DTPA available trace element concentrations in mg kg^{-1} in wastewater sludge and biochar.

Elements		RS	300 °C	400 °C	500 °C	700 °C
Cu	Mean	22.75	<0.1	14.75	17.25	<0.1
	SD	±4.64		±1.93	±2.49	
	RE			0.4	0.4	
Fe	Mean	467.5	842.5	390.00	342.5	212.5
	SD	±17.97	±158.44	±4.08	±15.47	±6.29
	RE		1.3	0.5	0.4	0.2
Mn	Mean	51.00	36.00	13.00	24.00	0.11
	SD	±10.68	±0.81	±0.70	±2.34	±0.01
	RE		0.5	0.2	0.3	0
Zn	Mean	297.5	142.5	83.5	52.5	0.11
	SD	±59.91	±4.78	±5.42	±5.85	±0.01
	RE		0.3	0.2	0.1	0
Cd	Mean	0.15	<0.1	0.20	<0.1	<0.1
	SD	±0.01		±0.01		
	RE			0.8		

RS = raw sludge; SD = standard deviation; RE = relative enrichment factor.

4. Conclusions

Pyrolysis temperature has significant effect on the chemical properties of the biochar produced from wastewater sludge in this work with important implications regarding their suitability as a soil amendment. A wide range of elements important for crop cultivation are present in the biochar, such as N, P, K and micronutrients. The study confirmed that the yield of biochar decreases with increasing pyrolysis temperature. The study also shows that wastewater sludge biochar produced at low temperatures (300 °C, 400 °C) is acidic whereas at high temperature (700 °C) it is alkaline in nature. This is an important finding as the agricultural use of biochar can have a twofold application. If the soil intended for biochar application is acidic in nature, then the biochars produced at 700 °C or higher temperatures can be used to neutralize the soil, improve soil fertility and sequester carbon. On the other hand biochars produced at lower temperatures might be suitable for alkaline soils to correct for alkalinity problems.

For the biochar produced in this work, the concentration of N and particularly in its available form for plant uptake was found to be very low and decreased with temperature. Attention is needed when biochars very low in mineral nitrogen are applied to agricultural and supplementation with nitrogenous fertilisers may be required for adequate plant nutrition. On the other hand, concentration of all micronutrients (Ca, Fe, Mg, S, Cu and Zn) as total elements was found to increase with increasing temperature. Pyrolysis temperature also had an effect on enrichment of heavy metals (Zn, Pb, Ni and Cd) in the produced biochar, which is important consideration as the heavy metals can bioaccumulate when biochars are applied to the soil. Arsenic and selenium in the wastewater sludge biochar used in this work were below the detection limit. However, DTPA-extractable concentrations of some of these elements were found to decrease with increasing pyrolysis temperature and therefore this indicates a tendency of these elements to become less available to plants.

Our results indicate there is a great potential to convert wastewater sludge to biochar in order to improve the management of this waste, reduce its transport costs and reduce the production volume. Produced biochar may serve as a valuable soil amendment by supplying plant nutrients and other benefits including carbon sequestration. Our results further highlight the potential to improve the quality, hence the agronomic value and minimize the potential harmful effects of the biochars by controlling the pyrolysis temperature. It is especially very important to have a better understanding of the mobility and bioavailability of the trace elements present in the biochar, before field trials are attempted.

Acknowledgements

The authors gratefully acknowledge the financial support for this research provided by the Higher Degree Research Unit, Macquarie University, Sydney, Australia. The authors also wish to thank the Sydney Water for supply of wastewater sludge samples for the study.

References

Bagreev, A., Bandosz, T.J., Locke, D.C., 2001. Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage derived fertilizer. Carbon 39, 1971–1979.

Barbarika, A., Lawrence, J.S., Colacicco, D., 1985. Factors affecting the mineralization of nitrogen in sewage sludge applied to soils. Soil Science Society of America Journal 49, 1403–1406.

Bridle, T.R., Pritchard, D., 2004. Energy and nutrient recovery from sewage sludge via pyrolysis. Water Science and Technology 50, 169–175.

Caballero, J.A., Front, R., Marcilla, A., Conesa, J.A., 1997. Characterization of sewage sludges by primary and secondary pyrolysis. Journal of Analytical and Applied Pyrolysis 40–41, 433–450.

Chan, K.Y., Xu, Z., 2009. Biochar: nutrient properties and their enhancement. In: Lehmann, Johannes, Joseph, Stephen (Eds.), Biochar for Environmental Management Science and Technology. Earthscan Publishing, UK.

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S., 2007. Assessing the agronomic values of contrasting char materials on Australian hardsetting soil. In: Proceedings of the Conference of the International Agrichar Initiative, 30 April–2 May 2007, Terrigal, NSW, Australia.

Clark, M.D., Gilmour, J.T., 1983. The effect of temperature on decomposition at optimum and saturated soil water contents. Soil Science Society of America Journal 47, 927–929.

Cogger, S.G., Forge, T.A., Neilsen, G.H., 2006. Biosolid recycling: nitrogen management and soil ecology. Canadian Journal of Soil Science 86, 613–620.

Gaskin, J.W., Steiner, C., Harris, K., Das, C., Bibens, B., 2008. Effect of low temperature pyrolysis conditions on biochar for agricultural use. Transactions of the ASABE 51, 2061–2069.

He, Y.D., Zhai, Y.B., Li, C.T.L., Yanf, F., Chen, L., Fan, X.P., Peng, W.F., Fu, Z.M., 2010. The fate of Cu, Zn, Pb and Cd during the pyrolysis of sewage sludge at different temperatures. Environmental Technology 31, 567–574.

Horne, P.A., Williams, P.T., 1996. Influence of temperature on the products from the flash pyrolysis of biomass. Fuel 75, 1051–1059.

Hospido, A., Moreira, M.T., Martin, M., Rigola, M., Feijoo, G., 2005. Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: anaerobic digestion versus thermal process. International Journal of Life Cycle Analysis 5, 336–345.

Hwang, I.H., Ouchi, Y., Matsuto, T., 2007. Characteristics of leachate from pyrolysis residue of sewage sludge. Chemosphere 68, 1913–1919.

Joao, C., Margarida, A., Olga, R., 1997. Effect of composted sewage sludge amendment on soil nitrogen and phosphorus availability. Communications in Soil Science and Plant Analysis 28, 1845–1857.

Koch, J., Kaminsky, W., 1993. Pyrolysis of a refinery sewage sludge. Erdöl, Kohle, Erdgas, Petrochemie 46, 323.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems – a review. Mitigation and Adaptation Strategies for Global Change 11, 403–427.

Magdoff, F.R., Chromec, F.W., 1977. Nitrogen mineralization from sewage sludge. Journal of Environmental Health A12, 191–201.

McBride, M.B., 1995. Toxic metal accumulation from agricultural use of sludges: are USEPA regulations protective. Journal of Environmental Quality 24, 5–18.

McLaughlin, M.J., 1984. Review – land application of sewage sludge: phosphorus considerations. South African Journal of Plant and Soil 1, 21–29.

McLaughlin, M.J., Champion, L., 1987. Sewage sludge as a phosphorus amendment for sesquioxic soils. Soil Science 143, 113–119.

Mulligan, C.J., Strezov, L., Strezov, V., 2010. Thermal decomposition of wheat straw and mallee residue under pyrolysis conditions. Energy & Fuels 24, 46–52.

Overcash, M., Sims, R.C., Sims, J.L., Nieman, J.K.C., 2005. Beneficial reuse and sustainability: the fate of organic compounds in land-applied waste. Journal of Environmental Quality 34, 29–41.

Parker, C.F., Sommers, L.E., 1983. Mineralisation of nitrogen in sewage sludges. Journal of Environmental Quality 12, 150–156.

Pastene, A.J., 1981. Factors Affecting the Crop Availability of Phosphorus in Sewage Sludge Amend Soils. Master thesis. University of Wisconsin.

Rayment, G.E., Higginson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata, ISBN 0 909605 68 8.

Shinogi, Y., 2004. Nutrient leaching from carbon products of sludge. In: ASAE/CSAE Annual International Meeting, Paper No. 044063, Ottawa, Ontario, Canada.

Singh, R.P., Agrawal, M., 2008. Potential benefits and risks of land application of sewage sludge. Waste Management 28, 347–358.

Sommers, L.E., 1977. Chemical composition of sewage sludges and analysis of their potential use as fertilizers. Journal of Environmental Quality 6 (2), 225–232.

Strezov, V., Evans, T.J., 2009. Thermal processing of paper sludge and characterization of its pyrolysis products. Waste Management 29, 1644–1648.

Sumner, M.E., 2000. Beneficial use of effluents, wastes and biosolids. Communications in Soil Science and Plant Analysis 31, 1701–1715.

Tsai, W.T., Lee, M.K., Chang, Y.M., 2006. Fast pyrolysis of rice straw, sugarcane bagasse and coconut shell in an induction heating reactor. Journal of Analytical and Applied Pyrolysis 76, 230–237.

Underwood, A.J., Chapman, M.G., 1989. GMAV5 for Windows. Institute of Marine Ecology, University of Sydney, Australia.